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Fetch Requirements near a Forest Edge

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Abstract Measurements on forest-atmosphere exchange should be executed some distance from the forest boundaries to be representative for this forest. In this study the minimum fetch at measuring height is estimated by analysing measurements just above a mixed forest stand near the edge. The objective was to gain insight in the development of the Equilibrium Layer (EL) after a transition in vegetation height; only wind and shear stress were considered. The variations in u*/u and wind speed gradients above the canopy, as a function of wind direction and fetch were analysed. In this canopy roughness layer, stability corrections are small due to the large roughness of the forest. An adapted version of the model of Klaassen (1992) was used to simulate fluxes as well as gradients above the forest.

It appeared that the disturbances from equilibrium arise not only from the forest edges, but also from the local changes in tree height between patches within the forest itself. A fetch:height ratio of 36 for the EL seemed appropriate for specific fetch directions at the site under study. This is in agreement with previous studies.

1 Introduction

To date, many meteorological studies have been performed of the surface layer in homogeneous terrain. The flow over these homogeneous surfaces can be described with similarity relations and is representative of the underlying surface. Just above a heterogeneous landscape however, the flow is not necessarily in equilibrium with the surface.

An important physical process near and above a heterogeneous terrain is the development of an Internal Boundary Layer (IBL). This IBL is the layer which grows in thickness, downwind of a discontinuity in some property of the surface, and roughly separates the flow characteristic of upstream conditions and that more characteristic of the new surface (Gardiner et al, 1995; Garrat, 1990).

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The growth of an IBL is more complex when the discontinuity in the surface includes a change in vegetation height, like a grass-forest transition. At the transition a change in surface roughness, porosity and displacement height will also be involved. At the transition the wind will partly be blown through the vegetation, and partly lifted up over the vegetation by pressure effects building up near the edge.

Within the IBL, the Equilibrium Layer (EL) can be defined as the layer above a new surface where the local stress is largely (say for 90%) in equilibrium with the underlying downstream surface (Garrat, 1990). For unstable conditions and a smooth-to-rough change, Bradley (1968) originally gave a conservative fetch:height ratio of 200 for the development of an EL, studying strips of vertical spikes with a roughness of 0.25 cm. Gash (1986), studying a 9.8 m mixed forest, gives a much more moderate fetch:height ratio for fluxes of between 16 and 27. Research from Kruijt (1994) downwind of a forest edge with an average height of 22 m, indicated that equilibrium is reached at a fetch:height ratio between 24 and 48. Irvine (1997) found a fetch:height ratio of 25 studying a 7.5 m high forest. These fetch:height ratios are stability-dependent; though in the canopy roughness layer above a rough forest, the stability corrections tend to be small.

The following question is as yet unsolved. If a fetch:height ratio would be independent of the difference in vegetation height, this ratio would be roughly identical in all studies. Whether this assumption is valid, is difficult to know due to the large uncertainties within each study.

According to Schmid (1994) fluxes adapt faster then scalars to a new surface by an order of magnitude. On the contrary Irvine, Gardiner and Hill (1997) state that fluxes require a longer fetch to adapt to a new surface than scalars.

The aim of this study is to determine the depth of the EL after a forest edge. Only wind and shear stress will be considered here. This will be performed by analysing the variations in u*/u and wind speed gradients, as a function of direction and fetch. The measurements are necessarily executed in the canopy roughness layer and close to the forest, with all theoretical limitations in mind, in order to analyse the disturbances of vegetation

transitions nearby.
We investigate the dependence of the EL depth to fetch, atmospheric stability and the length of surface transition. Also we aim to check whether the depth of the EL is equal for fluxes and scalars.

2 Site description

The measurement campaign has been executed in the "Bankenbosch" forest near Veenhuizen in the Northeast of the Netherlands (53°01'N, 6°25'W). The forest is bordered by the large Fochteloërveen bog area in the south and western direction. It consists of many small homogeneous patches of deciduous as well as coniferous tree species. These patches have a surface area varying between 3500 and 71000 m^2, giving the forest a total surface area of 1.2 km^2. Species vary to a considerable degree in height (4.2 to 28 m) and Leaf Area Index (1.3 to 6.1 m^2/m^2). The most prevailing species in declining order are: Beech (*Fagus Sylvatica*), Japanese Larch (*Larix Kaempferi*), Norway spruce (*Picea abies*), Douglas fir (*Pseudotsuga menziesii*) and Summer oak (*Quercus robur*). Throughout the forest, the soil layer consists of sand with a loam layer at roughly one meter underneath. The terrain itself is very flat. Figure 1a and 1b show an overview of the area with tower positions and tree characteristics. The patch surrounding the SLIMM- (Surface Layer Integration, Measuring and Modelling) tower is filled with Summer oak (*Quercus robur*). The patch is rather open, with an average tree height of 22.6 m and an average LAI of 2.5 m^2/m^2.
The underground consists mainly of grass species, blackberry (*Robus fruticosus L.*) and common polypody (*Polypodiaceae Vulgare L.*). The closest forest edge, at 150 m, lies to the North-north-west.
The measurement tower of the Winand Staring Centre (WSC) is situated 800 m west of the SLIMM site, with several tree patches in between. This patch is filled with Japanese Larch (*Larix Kaempferi*), with an average tree height of 19.7 m and an average LAI of 1.3 m^2/m^2 . The shortest distance towards the forest edge is 150 m, lying to the west.

3 Material and methods

The tower at the SLIMM site is 60 m high, three times the local tree height. The tower was equipped with ten cup anemometers at 6, 12, 18, 21, 23, 26, 30, 36, 46, & 60 m. Absolute psychrometers were mounted at the lowest four and the highest level. Four differential psychrometers for measurements were used between 21, 26, 36, 46, & 60 m. Incoming, outgoing, short-wave- and long-wave radiation components were measured with pyrano- and pyrgeometers (Kipp).

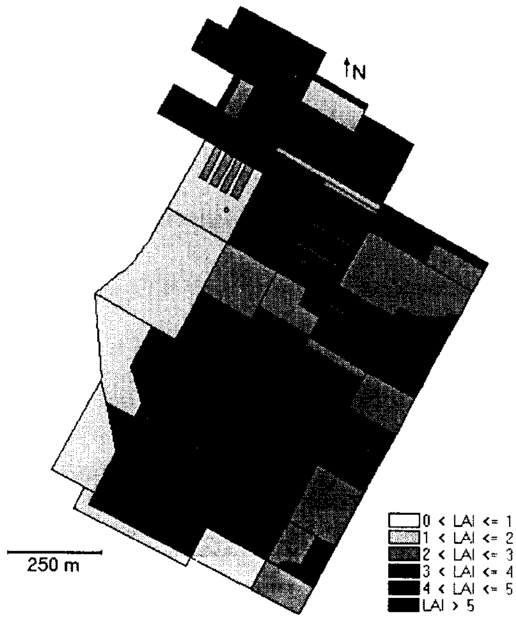

Figure 1a: The average Leaf Area Index (LAI) of the patches in the "Bankenbosch" wood. The SLIMM tower is marked with an +. The WSC tower is marked with an o.

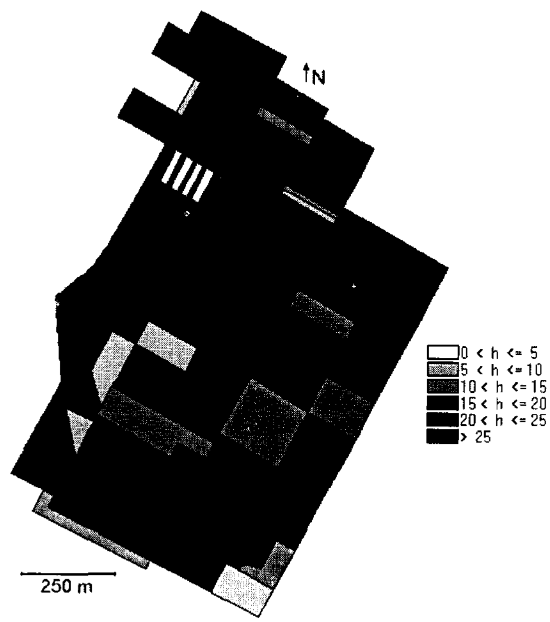

Figure 1b: The average tree height (m) of the patches in the "Bankenbosch" wood. The SLIMM tower is marked with an +. The WSC tower is marked with an o.

An infrared radiation thermometer (Heimann, KT15) mounted five metres above the canopy registered the average canopy temperature. An installed leaf wetness sensor denoted periods of rain or dew. The wind direction was measured at 25 and 60 m.
All instruments were sampled with a frequency of 0.2 Hz, and averaged over half an hour. Data were collected by six Campbell Cr10 loggers, which were weekly off loaded to a PC in a container office nearby. The transportation system existed of a glass fibre system in order to minimise quality loss. For more details we refer to Van Breugel (1996).

As we are especially interested in exchange processes, wind speed is transformed in a parameter related to turbulence. The variable (du/dz)/u, a normalised windspeed gradient, is an indication of local turbulence. Note that stability corrections are not incorporated with this variable. This variable still can be used for analysis, for close above a forest, stability corrections tend to be much smaller due to the high roughness of the vegetation.
For this analyses, the windspeed at a height of 21.4 and 25.8 m is used to calculate the variable (du/dz)/u. The relation between (du/dz)/u and u*/u is given by:

$$\frac{(\frac{du}{dz})}{u} = \frac{u^*}{u} * \frac{\Phi_m(\zeta)}{l_m} \tag{1}$$

where $\phi_m(\zeta)$ is a dimensionless stability parameter and l_m is the mixing length (m), which is allowed to deviate from k(z-d) over a heterogeneous surface. The parameter k is the Von Karman constant ($\approx$0.4), z is the average measurement height (m), and d the displacement height (m). The mixing length is a measure of turbulence to cause mixing (Stull, 1988). The vector u in (du/dz)/u is taken as the average of the wind speed at both levels.
At the WSC tower a 3d sonic anemometer and a fast hygrometer (Krypton) was measuring at a height of 27 m. At the tower were also mounted a cup anemometer (Vector), air thermometer and slow hygrometer (Vaisala), a pyranometer (Kipp) and a pyrgeometer (Kipp&Zonen). The tower system was powered with the aid of two sun collectors and a wind turbine. The data were processed in a HP100 palmtop and collected in a Campbell CR10 data logger. A description of the measurement site can be found in Elbers et al. (1996).
To analyse whether turbulence is disturbed near a forest edge, the measurements are compared to expected values for *homogeneous* surfaces. In these circumstances the ratio of u*/u is a function of height, roughness and stability:

$$\frac{u^*}{u} = \frac{k}{\ln(\frac{z-d}{z_o}) + \psi(\zeta)} \tag{2}$$

$\Psi(\zeta)$ is the integral stability correction. Theoretically, above a *homogeneous* forest surface and with *neutral* conditions, u*/u should be constant. With the local displacement height d of 14 m and roughness length z_0 of 2.2 m u*/u is calculated to be 0.223 (Eq 2). Note that roughness sublayer corrections (Wenzel et. al., 1997) influence the wind profile, but hardly influence normalised friction velocity.
The relationship between the turbulent diffussivity K_m and u* is the following:

$$K_m = \frac{l_m\ u^*}{\Phi_m(\zeta)} \tag{3}$$

The variable K_m (with the units $m^2\ s^{-1}$) describes the turbulent mixing according to the relative simple 'K-theory' or 'gradient transport theory'.
This study uses data from August 1996 from both measurement towers, and from September 1996 from the SLIMM database.

4 Model description

The surface layer model of Klaassen (1992) is used to simulate u*/u and wind speed gradients at a fetch downwind of a forest edge. The model is extended to incorporate differences in vegetation height within the forest. The model is two-dimensional with a first order mixing length closure. This mixing length l_m advects along the flow and adjusts slowly to the new surface. Adjustment rates for l_m were determined by empirical parameters, calibrated against measurements of Bradley (1968) and validated against measurements of Gash (1986). The model simulates the vegetation as several layers on top of each other where the wind can blow through. The forest edge is simulated with a change in roughness and porosity, though pressure effects are not implemented. The vegetation is assumed to be homogeneous in the lateral direction to satisfy two-dimensionality. The meteorological input of the model consists of the wind speed, temperature, relative humidity, and incoming radiation at the boundary layer height. Tree height and LAI of the forest patch are also needed. Five different wind directions have been selected, with a large variation in fetch and characteristics of the upwind surface. The model initialisation starts with the calculation of profiles of wind speed, temperature and humidity above a homogeneous grass site.

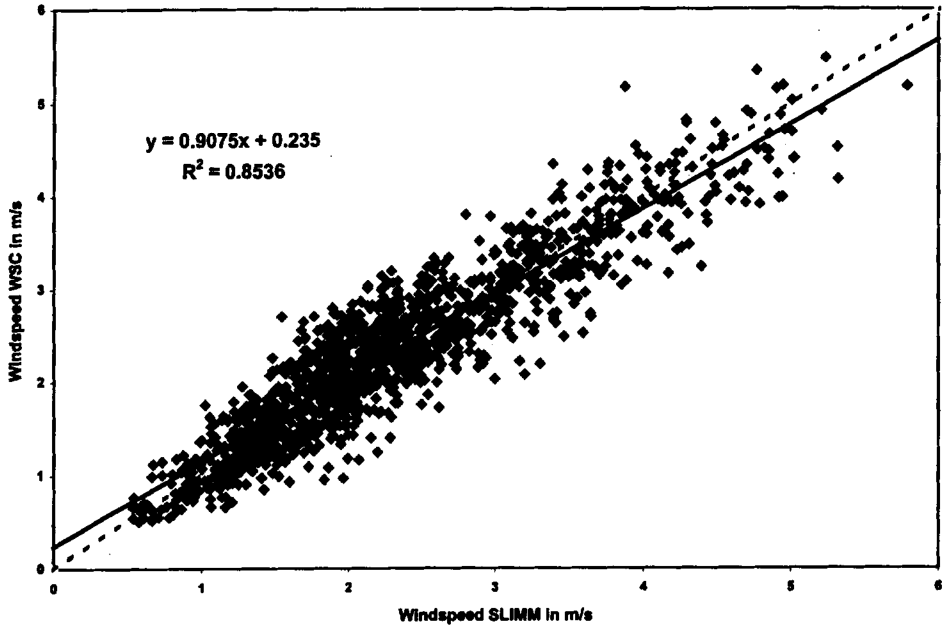

Figure 2: The wind speed at the SLIMM site against the wind speed at the WSC site in (m s^{-1}).

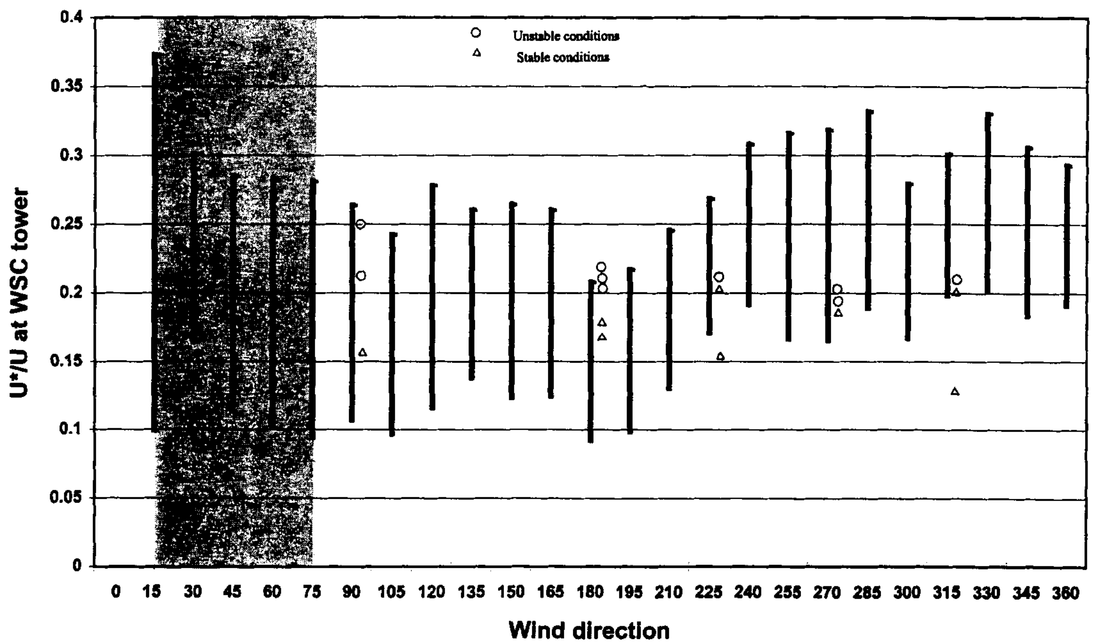

Figure 3: The variable u*/u (m s^{-1}) as a function of wind direction (°), as measured at the WSC site. Model simulations are included.

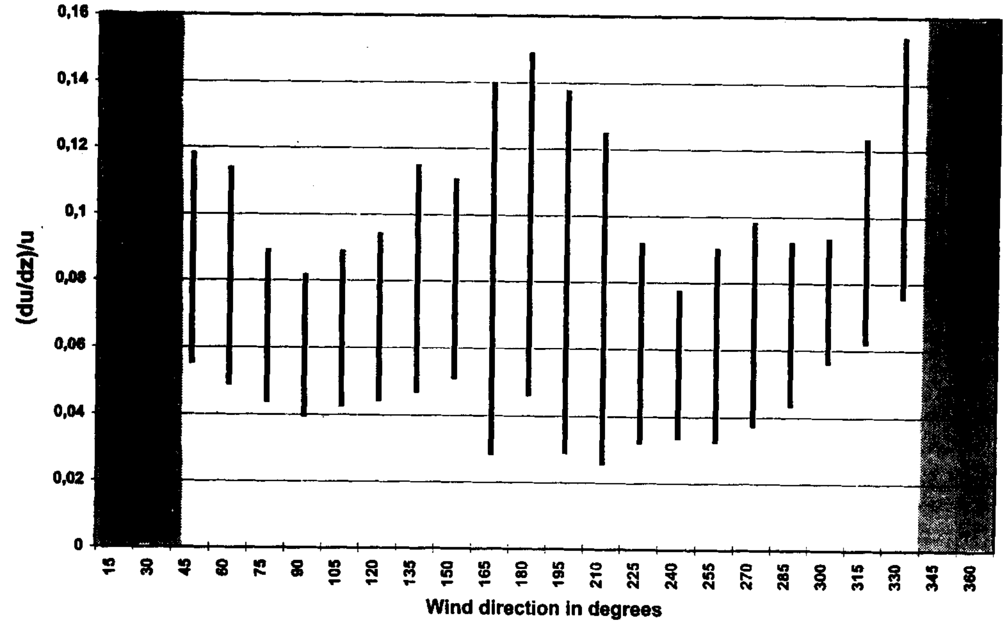

Figure 4: The variable (du/dz)/u (m^{-1}) versus wind direction (°), as measured at the SLIMM site.

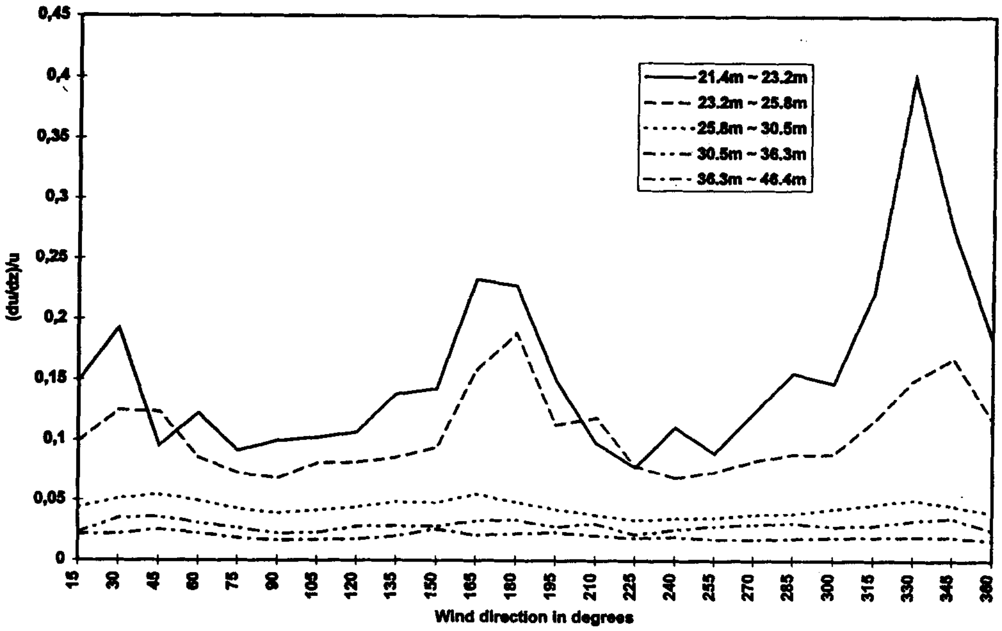

Figure 5: The variable (du/dz)/u (m^{-1}) as a function of height (m) and wind direction (°) at the SLIMM site.

5 Results and analysis

Figure 2 shows the wind speed (m s^{-1}) at the SLIMM site against its counterpart at the WSC site. The wind speed at the SLIMM site was measured at 25.8m above a 22.6m forest (d 13.5m), while at the WSC site it was measured at a height of 25m above a 19.7 m forest (d 12.5 m). Wind speeds lower then 0.5 m s^{-1} have been excluded from the analysis because of stalling errors. The curve approximately fits the 1:1 line. The high correlation between the wind speed measurements at both sites suggests only a small influence of terrain heterogeneities on wind speed above the forest. The friction velocities between the respective towers agree to a much lesser degree. In order to study the relation between the differences in u* and the presence of local terrain influences, an analysis of the dependence of wind speed normalised u* on wind direction is made.
Figure 3 shows the dependency of u*/u against the wind direction (in °), as measured at the WSC site. The measurements are denoted as averages ± standard deviation bars, given for segments of 15° wind direction. A dependency of stability with wind direction was not observed (not shown in a Figure).
Around 105° and 180° u*/u reaches a local minimum. This was caused by the larger tree heights upstream in these directions; being 25.4 m around 105°; in the southern direction the tree height in the patch of the measurement tower decreased locally by approximately two metres, causing a relative height difference of two metres at the edge of this patch.
A local maximum occurred between 225° and 285° and between 315° and 345°. The first maximum is related to the presence of the nearby forest edge 150 m away at 270°. The second maximum between 315° and 345° is attributed to the small patches of 4.5 m high *Pinus Sylvestris*.
The magnitude of the model simulation of u*/u, as shown in Figure 3, agrees reasonably well with the data, though the trend with wind direction is not clearly followed. The simulations increase with decreasing stability as expected. Though the individual patches of the forest were implemented, the model output does not follow the same trends as the data. This can be explained by a too slow adapting mixing length in this model. Hence, the advected u*/u changes too slow as well.
Figure 4 shows the dependency of (du/dz)/u (in m^{-1}) versus wind direction (in °) where du/dz is evaluated between levels at 21.4 and 25.8 m at the SLIMM site. Maxima were found between 165°and 210° and between 315° and 45°. Theoretically the maxima and minima in the figure might be caused by the limited measurement heights, which are well within the roughness layer. As the individual patches are rather homogeneous, the most likely cause is a transition in vegetation height between bordering patches. The first maximum is highly correlated with the presence of a patch of *Pseudotsuga menziesii* south of the measurement site, which was 6.6 m lower. The second maximum can be explained by the nearby presence of the forest edge in the northern direction. The local minimum between 360° and 15° can not be explained physically, and is accordingly attributed to a natural variation in the signal.
Between 315 and 345° the maximum in (du/dz)/u has a value of about 160% of the average value. According to Gash (1986), u*/u adapts itself quickly to the new surface. As u*/u adapts quickly, and a dependence of stability on wind direction does not occur, the mixing length has to decrease locally (see eq.1). In our situation the fetch in the region of the peak in u*/u (225-300°) is within 500 m, which corresponds with a fetch:height ratio of 36.
Figure 5 shows the height-dependency of (du/dz)/u. At levels above the canopy, below 25.8 metres, a large fluctuation in the variable with wind direction is found. This is caused by local differences in vegetation characteristics. At higher levels, this variation is decreasing as expected, though it still can amount to 60% between 30.5 and 36.3 metres.
The statement of Gash (1986) that u*/u adapts itself quickly to the new underlying surface seems not in agreement with the findings of Irvine, Gardiner and Hill, (1997) who state that fluxes take longer to adapt to a new surface than scalars. This contradiction might be caused by the limitations of measurement techniques which, compared to numerical models on this scale, possess a crude statistical accuracy.
According to Kruijt (1994) the turbulent diffussivity K_m can be strongly decreased to 60% of the equilibrium value, close to the forest edge. Assume that above a forest over a certain period, the stability parameter ϕ_m is independent of wind direction, so different fetches can be compared in these measurements. This decreasing K_m then implies a decreasing mixing length eq. (1). A decreased mixing length would explain why the directional disturbance of (du/dz)/u exceeds u*/u. This is in agreement with Schmid (1994) who states that the source areas for scalars are larger, by an order of magnitude, then the source areas for fluxes.

6 Conclusions

According to literature, the EL above a forest will be formed with a fetch:height ratio of between 24 and 48, starting at the zero-plane displacement. With the conditions at the WSC measuring site, a fetch of 500 m is required before the measurement height would be within this layer. This coincides with a fetch:height ratio of 36. The theory seems to fit with

observations in the southwest direction, where fetches less then 500 m coincide with an increasing u*/u. At the northwest direction however, the area consists, next to the absolute forest edge, of several small patches next to each other, with strongly deviating average tree heights. These conditions make the evaluation of fetch requirements in this direction more complex. This study makes clear that the influence of a local change in tree height between patches within the forest itself can have a large impact on the measured variables.
The model of Klaassen on average agrees with the measurements. The trends in the data, however, are not simulated by the model. The modelled mixing length, which adapts itself too slow to new circumstances is the most conceivable cause.
At the SLIMM site the minimum required fetch to measure scalars within the EL is estimated to be 625 m. The corresponding fetch:height ratio for a scalar EL is 73. This is more then the ratio for fluxes, in agreement with Schmid (1994).
Kruijt (1994) states in his study that the fetch:height ratio of the EL might be vegetation-height dependent. The present study suggests moreover that empirical fetch:height ratios are influenced by measurement accuracy. Moreover the fractional change in windspeed is small as compared to the disturbance in friction velocity. So disturbances of friction velocity can be detected more easily and may lead to a suggestion that wind speed is quickly adjusting to the new surface.

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